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RESEARCH ARTICLE

A framework to integrate multifunctionality analyses into green infrastructure planning

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Abstract

Context Green infrastructure (GI) has become an integral part of the process leading toward urban sustainability because it provides multiple ecosystem services that contribute to urban ecosystems and human health. Planners and managers have therefore attempted to understand and improve GI multifunctionality.

Objectives This study has characterized and mapped GI multifunctionality in the Fengtai District of Beijing based on the ecosystem services (ES) perspective and has developed an adaptive model to improve its multifunctionality. The study has aimed to: (1) assess and map GI multifunctional degree, (2) characterize GI multifunctional types, and (3) propose adaptive solutions based on characterization of GI multifunctional types.

Methods Biophysical models and social questionnaires were used to quantify and map ES, ES hotspots, and ES bundles to identify the degree of multifunctionality and characterize GI multifunctional types. An adaptive model was designed to improve GI multifunctionality for local planning and design practice.

Results Three GI multifunctional degrees were mapped, and areas with high multifunctional degree were found to account for only 5.55% of the study area. Seven GI multifunctional types were identified by the distinct heterogeneity of their compositions and function sets. These types of GI also implied different improvement strategies for GI planning and design practice. The adaptive model offers integrated solutions for preserving, restoring, and embedding levels that correspond to the characterization of GI multifunctional types.

Conclusions The ES-based framework proposed in this paper integrates multifunctionality analyses and can be helpful to urban planners and designers in adaptive GI planning.

Keywords China · Green infrastructure · Multifunctionality · Ecosystem service · Adaptive planning and design

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Yanan Wang and Qing Chang have contributed equally to this work.

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Introduction

The past decades of rapid urbanization with consequent loss and degradation of green space have caused various environmental problems such as habitat fragmentation, biodiversity loss, air pollution, heat islands, and heat waves (Grimm et al. 2008; Cardinale et al. 2012; Adams 2014), as well as affecting human health adversely (Tzoulas et al. 2007). To meet this challenge, the concept of green infrastructure (GI) was introduced to achieve urban sustainability (Mell et al. 2013). As an interconnected network consisting of parks, woodlands, wetlands, green roofs, and other green spaces within, around, and between urban areas, GI is expected to provide a diversity of functions to residents, the economy, and the local environment. These include supporting native species, maintaining natural ecological processes, sustaining air, water, and soil resources, offering food and materials, and contributing to human well-being (Benedict and McMahon 2002; Tzoulas et al. 2007; Hansen and Pauleit 2014). Through these multiple GI functions, i.e., its attribute of multifunctionality, GI has contributed to urban sustainability at all spatial scales for decades. For example, a state-, province-, and city-wide network of large ecologically significant hubs bound together by greenway links was identified as a place to strive for ecological functions, biodiversity promotion on land and in the water, and multi-faceted and walkable amenity provision (Mell 2009; Chang et al. 2015; Artmann et al. 2017). This approach has been illustrated by the GI strategy of Maryland State University (Weber et al. 2006), the green-future strategy of Seattle in the United States (Rottle 2006), the GI strategy of Manchester in England (Manchester City Council 2015), and the greenway network of the Pearl River Delta in China (Liu et al. 2019). GI patches, such as the parks designed by Frederick Law Olmsted in the United States (Benedict and McMahon 2002) and even patches as small as domestic gardens and trackside vegetation along railways, can also contribute to structural landscape diversity and water and climate regulation (Cameron et al. 2012; Hoerbinger et al. 2018). Hence, increasing GI quality and multifunctionality is becoming a coherent planning strategy (Hansen et al. 2019), and many cities are struggling to find theoretical support and coordination approaches to implement comprehensive citywide GI planning.

As an important topic in the field of landscape ecology, multifunctionality has also attracted increasing attention among academics and is seen to represent the optimal objective of landscape management for sustainability (Wu et al. 2013a, b; Wu 2019). The concept of ecosystem services (ES) is frequently used in the literature to represent GI functions (Lovell and Taylor 2013). Multifunctionality is described as the capacity of green infrastructure to provide multiple ES (Hansen and Pauleit 2014). Functions are discussed as "intermediate products" of ES and the origin of services for humans (Boyd and Banzhaf 2007; Haase et al. 2012). ES mapping can be a powerful tool for understanding the characteristics of multifunctionality (Raymond et al. 2009; Ryan 2011), enabling localization of components with high multifunctional degree (hotspots) (Bryan et al. 2010) and facilitating effective analysis of interrelations among multiple functions (Nelson et al. 2009). Several researchers have mapped ES bundles on a regional scale to provide direction for GI spatial planning (Raudsepp-Hearne et al. 2010; Peng et al. 2017), proposed type-specific management strategies within which tradeoffs could be minimized and synergies maximized (Quintas-Soriano et al. 2014; Vannier et al. 2019), as well as identifying critical focal areas for decision-making (Plieninger et al. 2013; Peng et al. 2016). However, because most of these studies were conducted at relatively large scales (regional or continental) (Malinga et al. 2015), they have limited usefulness in guiding practices in urban areas, where areas of high demand for multiple functions are commonly mismatched with areas of high capacity for multiple function supply (Baró et al. 2015).

GI multifunctionality in urban areas has been frequently mentioned in the literature in recent years (Herzog 2016; Meerow and Newell 2017). Although a growing body of evidence indicates that GI planning involving greening projects has various specific functions and is likely to benefit urban residents (Lovell and Taylor 2013), few studies have mapped multiple functions and focused on their synergies and tradeoffs (Pulighe et al. 2016; Meerow and Newell 2017; Meerow 2020). It has also been uncommon to consider these multiple functions as part of a wider GI network (Hansen et al. 2019). Consequently, there is an apparent knowledge gap in applying GI multifunctional analysis to multi-scale planning and design practice (Schäffler and Swilling 2013). Although spatially explicit and site-specific information about GI multifunctionality at the whole city level would be helpful for GI master planning, guidance in the design and management of GI projects at the site level can deliver pragmatic adaptive solutions. Without a clear understanding of the characteristics and relationship of multiple GI functions across scales, urban planners may be unable to make multifunction-oriented and sustainable GI decisions efficiently. In some cases, the modular design mode may even lead to a case where some GI elements are not directly interlinked and are inefficient in multiple function supply (Artmann et al. 2017; Liu et al. 2019). Empirical data, tools, and guiding principles to facilitate multiple GI functions from city to local scale are currently lacking. Clearly, there is a need to analyze multifunctionality by taking GI as a whole entity to help us understand the synergies and tradeoffs among multiple functions (Sussams et al. 2015; Mexia et al. 2018) and to build bridges between multifunctional analyses using GI decision-making.

In China, an ecological civilization has been written into the Constitution as the ideological framework for the country's environmental policies, laws, and education (Hansen et al. 2018). The GI strategy has been promoted by the national policy of ecological civilization. For example, in Beijing, various GI development projects have been launched to improve the quality and quantity of green spaces, such as the Greenbelt Program in 2000 (Yang and Zhou 2007), Country Park Circle Projects in 2007 (Gong et al. 2015), and the Plain Afforestation Project in 2012 (Yu et al. 2018). Although more and more new parks are under construction or have been constructed in China, in some places it seems that a radical movement seeking short-term successes and quick benefits has arisen (Wang 2018). This development goes against the long-term environmental protection goal, which involves coordination between central and local governments, supervision of environmental protection bureaus, engagement of the science community, and support from society (Hansen et al. 2018). Communication between ecological science and planning practices will demonstrate the possibility and relevance of science for GI decision-making.

To understand the multifunctional role of these GI entities, this paper uses the Fengtai District of Beijing as a case study to assess the integrated ES of a GI network and analyze the relationships among ES. It will evaluate GI multifunctionality and develop a conceptual framework that links urban ecological analysis with local GI design practices. Specifically, this paper has three main objectives: (1) to assess and map the degree of GI multifunctionality, (2) to identify and classify the multifunctional types of GI, and (3) to propose adaptive design and planning solutions for different GI multifunctional types to improve the multifunctionality of the GI network.

Methodology

Study area

Located in the southwestern part of Beijing, the Fengtai District is one of the city's sub-centers (Fig. 1). The landscape is high in the northwest and low in the southeast, with an area of 305.8 km^2, and the Yongding River flows through from north to south. The eastern part of the Fengtai District is part of the core area of Beijing, with high population and construction density, whereas the western part is in the transition zone between Xishan Mountain and the North China plain, with ample hills and farmland. The GI elements of Fengtai are distributed across the built-up areas (Fig. 1). Despite plain afforestation projects and urban renovation programs that have been implemented since the early 21st Century, the GI pattern in Fengtai has two major weaknesses: fragmentation in the west, and discontinuity in the east. A plan is in place to restore nearly ten thousand hectares of green space in Beijing before 2022 (People's Government of Beijing Municipality 2019). New parks, woodlands, and wetlands will be embedded, along with renovation of shantytowns and old residential communities. Therefore, urban planners and designers urgently need to understand GI multifunctional characteristics to make appropriate decisions about where and how to enhance, restore, and embed GI elements in a sustainable way.

Data collection

The data used to assess GI functions were obtained and processed for this study as follows. Remote-sensing images of Fengtai District in 2017 were obtained from Landsat-8 satellite imagery (identified by path 123, row 32, and obtained on September 12), and the data

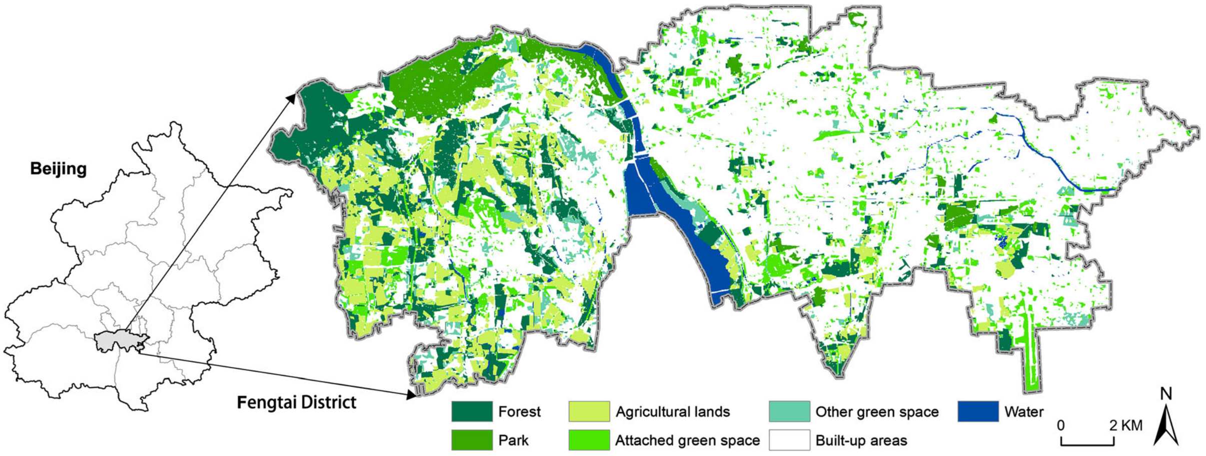


Fig. 1 Localization of GI elements in the study area

were downloaded from https://www.gscloud.cn/. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) data at 30 m resolution were downloaded from https://www.gdem.aster.ersdac.or.jp/search.jsp. Normalized Difference Vegetation Index (NDVI) and land surface temperature (LST) data were then calculated from each Landsat-8 image. Soil constituent distribution maps were downloaded from the Soil Information System of China. Annual precipitation and annual average temperature data were downloaded from the National Meteorological Information Center (https://data.cma.cn/) with the locations of meteorological stations, and kriging interpolation was used to obtain the spatial distribution.

Land use/land cover (LULC) data were also obtained, and the level of GI was classified into six types by combining remote-sensing image interpretation and green space survey data from the Gardening and Greening Bureau of Fengtai (Fig. 1). The accuracy of the land-cover types was verified by checking 400 randomly sampled points. The ground truth of the land-cover type at each sampling point was determined from Google Earth images, and the Kappa statistic of the classification was 86.67%. The GI types were determined with reference to the Ministry of Housing and Urban-Rural Development in China (the 'Chinese Urban Green Space Classification Standard', No. CJJT 85-2017):

Forest [FO]	Natural and planted forests in suburban areas.
Parks [PA]	Parks or gardens including zoological gardens, botanical gardens, historical gardens, heritage parks, theme parks, and so forth.
Agricultural lands [AL]	Cropland, orchards, and other productive lands.
Attached green space [AG]	Distributed in urban built-up areas such as commercial, residential, industrial, and transportation land and green belts.
Other green space [OG]	Consisting of suburban vegetated areas and ecological land.
Water [WA]	Includes rivers, pools, wetlands, irrigation channels, and so forth.

Methods

GI multifunctionality was evaluated through the spatial overlapping frequency of ES from GI and spatial bundles of ES. The spatial overlapping frequency of ES from GI was defined as the multifunctional degree of the GI, and spatial bundles of ES were determined from the multifunctional type of the GI. Figure 2 shows the steps of this procedure, which included assessing ES, identifying spatial ES hotspots from the GI, mapping GI multifunctional degree, classifying GI multifunctional types, and proposing adaptive design solutions to improve GI multifunctionality.

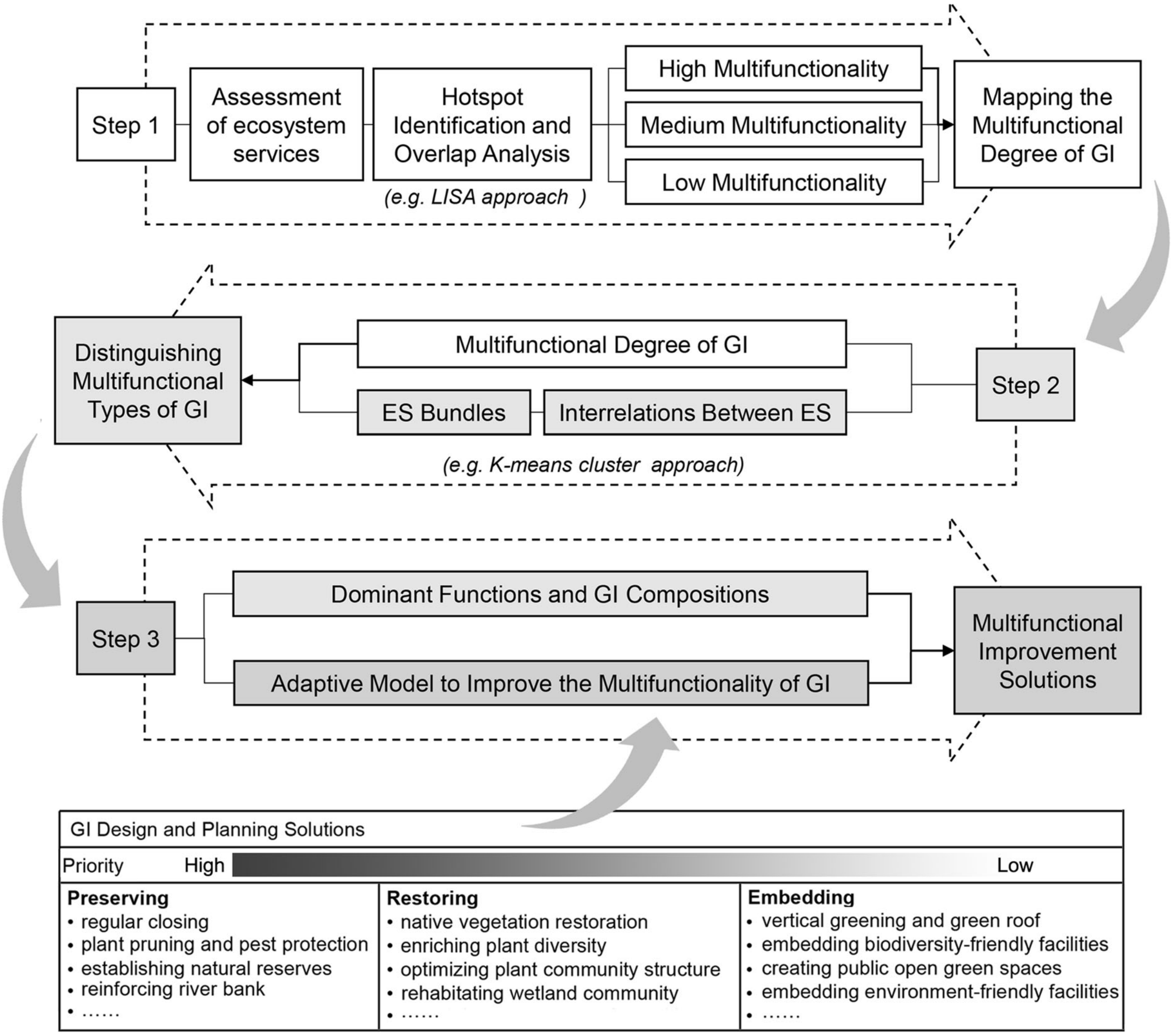


Fig. 2 Study procedure and steps

Mapping GI functions

The selection of functions investigated in this study enabled analysis of a range of supporting, regulating, provisioning, and cultural services of relevance to the study area. Because it was not possible to cover the whole diversity of ES within one study, a range of six key functions were selected (Table 1). As one of the sub-center districts of Beijing, the eastern part of Fengtai has been intensively built up. Therefore, this study first chose urban heat island mitigation (UM), risk mitigation (RM), and recreation (RE) functions. These functions are essential to urban sustainability and human well-being. Besides, Fengtai set forth plans to achieve biodiversity recovery, cultivated land protection, and sustainable water use in the Territory Development Plan before 2035 (People's Government of Beijing Municipality 2017), and therefore functions such as habitat support (HS), water conservation (WC), and food and material provision (FP) should be chosen in analyses. The six main functions were assessed spatially and explicitly through experiential methods. Table 1 provides an overview of the ES assessment methods and indicators and a brief description of the main data sources. The assessment results for each grid cell were standardized as numbers from 0 to 1. Detailed information about the data resources is listed in the Appendix.

Table 1 Indicators and methods for ES assessment

ES	Description	Indicators	Methods	Main data resources
Supporting service				
Habitat supporting (HS)	The capacity to support the lives of flora and fauna	The evaluation result of the Habitat Quality (IHQ) module of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model	Factors including constructed area, highways and railways are chosen as the threat to habitat quanlity, and focus species represented by *Tamias sibiricus*, *Parus venustulus* and *Ardeola bacchus*. Details on parameter setting are referred to the Invest User's Guide, can be found in appendix	Invest User's Guide; details of focus species of Fengtai from Zhao (2014) and Zhou (2010); distributions of highways and railways from Wu et al. (2013a, b)
Regulating service				
Water	conservation (WC)	The relative capacity to reduce soil erosion, regulate runoff, and increase available water resources	The evaluation result of the Water Yield (IWY) module of the InVEST model	The factors including annual precipitation, annual average temperature and the soil composition were calculated in the IWY module
National	Meteorological Information Center and Soil Information System of China			
Urban heat island mitigation (UM)	The capacity to mitigate the urban heat island	The difference between land surface temperature of GI and built-up areas	U = LST—T_C LST = Land surface temperatures of each GI unit, which is derived using Landsat-8 image in September 2017 T_C = Average Land surface temperature of built-up areas	Land Surface Temperature (LST) data were calculated from Landsat-8 image
Risk mitigation (RM)	The relative capacity to mitigate earthquake, landslide and traffic noise	Distance-weighted disaster risk reduction score	$R = \sum(S/D)$ S = The relative score of each GI to reduce each risk in a certain distance D = The distance of GI to each risk, which includes landslide, earthquake and traffic noise	Distribution of hazardous areas of landslide, seismic fault zones, railways and highways are from Sun et al. (2017), Ni et al. (2018) and Wu et al. (2013a, b) respectively
Provisioning service				
Food & material provision (FP)	The capacity to produce grain, vegetable and fruit as well as wood	The NDVI-weighted food and material production	$C = NDVI \times P$ NDVI = The Normalized Difference Vegetation Index that ranges from zero to one P = Annual production of grain, vegetable, fruit and woods	Statistical Yearbooks (2015, 2016 and 2017) of Fengtai (Beijing Municipal Bureau of Statistics 2019)
Cultural service				

Table 1 continued

ES	Description	Indicators	Methods	Main data resources
Recreation (RE)	The relative capacity for dwellers' recreation and leisure	Population-weighted recreational value score	S = T × D T = The standardized recreational value scores of each GI type by willingness to pay (WTP) questionnaires D = The standardized population density of each sub-district that ranges from zero to one	Statistical Yearbooks (2015,2016 and 2017) of Fengtai (Beijing Municipal Bureau of Statistics 2019) Details about the WTP questionnaires can be found in appendix

Details can be found in the Appendix

Identifying spatial GI function hotspots

In this study, spatial hotspots were identified to depict the spatial ranges of each function provided by GI elements. GI function hotspots consisting of spatial clusters and spatial outliers (Fig. 3) were identified through local spatial autocorrelation analysis (LISA), which can represent the spatial association characteristics of ES (Qiu and Turner 2013). A spatial cluster is a high-high cluster in which a grid cell with a high ES value is surrounded by others with high ES values, and a spatial outlier is a high-low outlier where a grid cell with high ES value is surrounded by others with low ES values (Fig. 3). The local Moran's *I* statistic, which measures the extent of significant spatial clustering of similar values around an observation grid cell (Anselin 1995), was used and can be calculated as follows:

$$I_i = \frac{(x_i - \mu)}{m_0} \sum_j w_{ij}(x_i - \mu)$$

$$m_0 = \sum_i (x_i - x)^2 / \mathrm{n}$$

where x_i is the standardized ES value of grid cell i, μ is the mean standardized ES value of all grid cells, and the summation over j is such that all the neighboring grid cells of grid cell i are included. A high positive local Moran's *I* value implies that the location under study has similarly high or low values as its neighbors, and therefore the location is a spatial cluster. Spatial clusters include high–high clusters and low–low clusters (Fig. 3). A high negative local Moran's *I* value means that the location under study is a spatial outlier that is obviously different from its surrounding locations (Lalor and Zhang 2001). Spatial outliers include high–low and low–high outliers, as shown in Fig. 3. In this study, to meet the need for GI design practices at local scale, the locations for the local Moran's *I* statistic were uniformized to 200 m grid cells, each with an area of 4 ha, resulting in 8068 grid

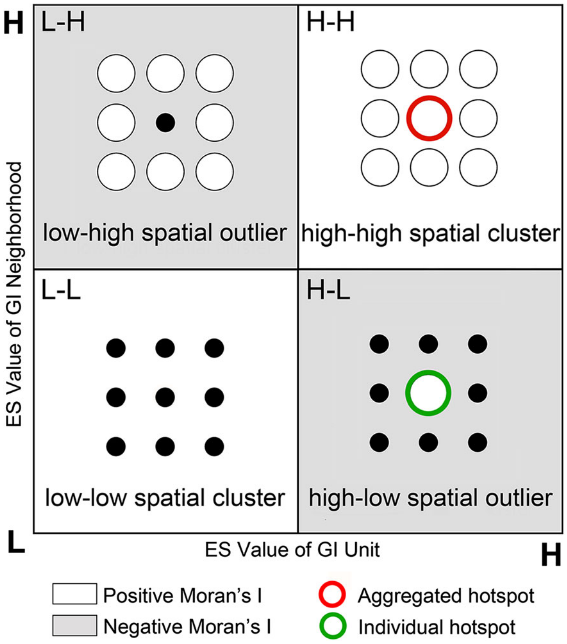


Fig. 3 Diagram to identify GI function hotspots

cells in total. The grid cells identified as spatial hotspots on each single ES map were coded as 1, and the remaining grid cells were set to 0.

Grading the GI multifunctional degree

Based on an overlaying spatial hotspot map of each ES from the GI, the multifunctional degrees in the GI was identified and mapped with the support of a geographical information system. Those grid cells where more than three types of spatial hotspots overlapped with each other, all of which represented high overlapping frequency of GI functions, were mapped as high GI multifunctionality cells. Cells were mapped as low GI multifunctionality when only one type of spatial hotspot was present. Cells between these two cases were mapped as medium GI multifunctionality.

Distinguishing GI multifunctional types

For cells with the same multifunctional degree, spatial groups in which ES co-occur might be different from each other. Therefore, ES bundles were used to distinguish the types of GI multifunctionality. The ES bundle analysis included identifying ES associations and partitioning each multifunctional degree into internally consistent spatial cell groups in terms of ES supply (Vannier et al. 2019).

To analyze ES associations, first, Spearman's rank correlation coefficient was used to reveal the relationships between ES pairs for all cells ($N = 8068$) in the study area. Correlation coefficients were classified as strong when $|r| \geq 0.5$, as moderate when $|r|$ was > 0.3 and < 0.5, and as weak when $|r| \leq 0.3$ (Fagerholm et al. 2012). The significant positive or negative correlations ($p < 0.05$) between two ES were considered to have tradeoffs or synergies, whereas non-significant correlations indicated no or extremely weak interaction. Next, based on principal component analysis (PCA) (Marsboom et al. 2018), ES associations in each multifunctional degree were identified through the main explanatory factors of the variability and distribution of the six ES values. The Kaiser–Meyer–Olkin test values of high, medium, and low multifunctional degree were 0.549, 0.731, and 0.713 respectively, and the significance of the Bartlett's test value of all three degrees was 0, indicating that the ES data met the requirements of principal component analysis ($\text{KMO} > 0.5,\ p < 0.05$). K-means cluster analysis was then used to identify spatial groups of cells with similar sets of ES in each multifunctional degree, i.e., bundles, where tradeoffs and synergies between ES were consistent (Raudsepp-Hearne et al. 2010). To ensure a reliable explanation of the variance of multiple ES, the number of clusters was selected based on the number of principal components with eigenvalues greater than 1. Finally, radar diagrams were used to visualize the multifunctional types.

Designing the adaptive model to improve GI multifunctionality

Under the adaptive model, planning and design can be understood as a hypothesis of how a project will influence particular landscape functions (Ahern 2011). In this study, an adaptive model of GI planning and design was designed to improve GI multifunctionality (Fig. 2). Potential planning and design solutions for enhancing GI quality were hierarchically packed as three levels: preserving, restoring, and embedding, and some example actions were provided for each level. By working in relationship with the locations of the multifunctional types, urban planners and designers might select more adaptive actions or measures according to the priority of each solution level. To improve GI multifunctionality for any location, solutions on the preservation level have priority over those on the restoration and embedding levels.

Results

Multifunctional degree and its GI spatial pattern characteristics

Spatial GI function hotspots

The supply of each GI function exhibited a distinct spatial pattern in the study area (Fig. 4). Urban heat island mitigation, risk mitigation, and recreation delivered by GI elements were distributed extensively across the study area, but in markedly different spatial patterns. Urban heat island mitigation exhibited higher values aggregated in the northwestern area and scattered in the southern area and was characterized by large areas of green patches such as woodlands, croplands, or water bodies. However, high-risk mitigation and recreation values were located more in the

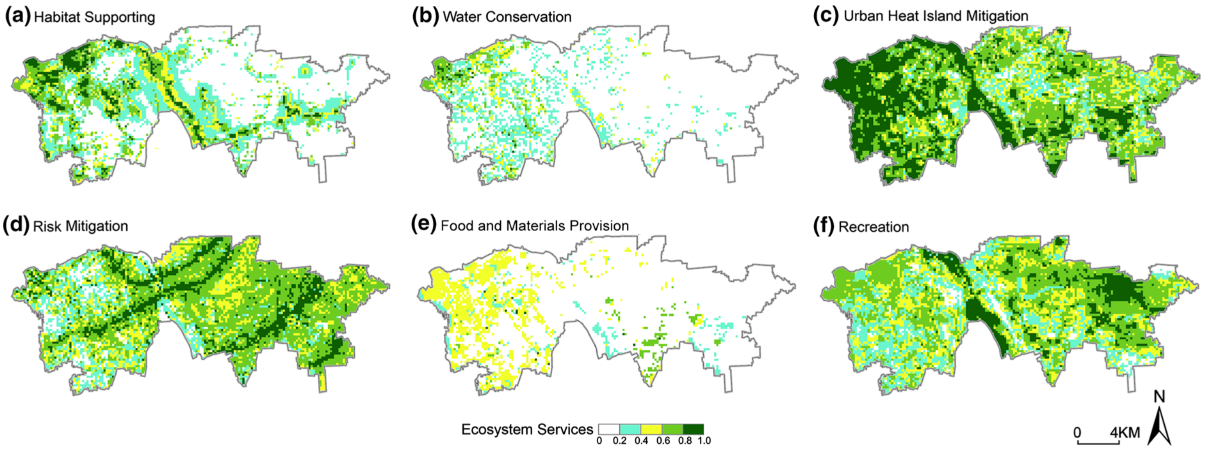


Fig. 4 Spatial GI function distribution

eastern area, with high hazard sources and high population density in a linear and patchy pattern respectively. In contrast, habitat support, food and material provision, and water conservation were mainly distributed in the western and northern areas that were characterized by higher altitudes and diverse green elements corresponding with forest, agricultural lands, and large parks. In this case, the levels of these three functions decreased from the hilly area in the northwest to the high-density built-up area in the east, and their maximum values overlapped.

The spatial hotspots of each GI function were clustered rather than randomly distributed (Fig. 5). Differences among these hotspots are also shown spatially. Aggregated hotspots of habitat support and urban heat island mitigation from the GI overlapped in the west and along the Yongding River (Fig. 5a, c), whereas water conservation hotspots overlaid those of food and material provision only in the west (Fig. 5b, d). In contrast, risk mitigation hotspots were partly overlaid by recreation hotspots in the east (Fig. 5e, f), most of which presented high population density and corresponded to the above four types of ES hotspots.

Multifunctional degree of GI

Mapping GI multifunctional degree based on overlaying spatial hotspots resulted in an unambiguous spatial pattern in the study area (Table 2). Spatial GI function hotspots covered 55.60% of the study area. Areas with high GI multifunctionality accounted for only 5.55% of the study area and were mainly

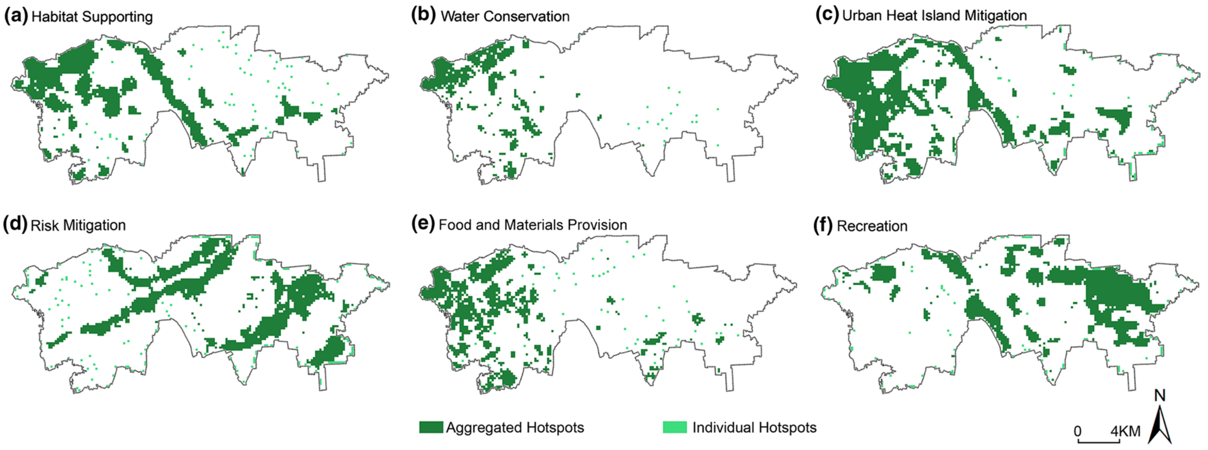
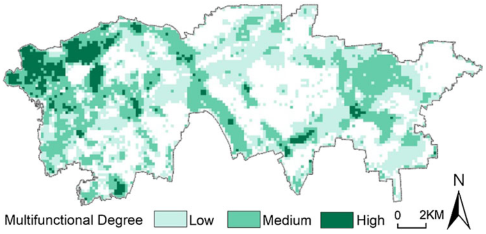


Fig. 5 Spatial distribution of GI function hotspots

Table 2 Map and statistics of areas with different multifunctional degree

Multifunctional degree of GI	Area ratio	Area ratio of compositions in the multifunctional degrees						
		FO	PA	AL	AG	OG	WA	BU
	5.55%	27.13%	52.24%	8.74%	2.47%	1.79%	1.79%	5.83%
	22.53%	9.71%	14.68%	19.16%	7.62%	4.83%	7.37%	36.64%
	27.52%	1.69%	7.60%	8.17%	8.77%	5.04%	1.00%	67.72%
Total spatial hotspots of ES from GI	55.60%	15.35%	7.48%	12.87%	7.36%	4.42%	3.92%	48.61%

distributed in the northwestern hilly area at higher altitude and scattered in the southern area; these highly multifunctional areas were characterized by a high percentage of parks and forests. Areas with medium and low GI multifunctionality accounted for 22.53% and 27.52% of the study area, respectively, and were distributed extensively across the study area, but with different spatial aggregation patterns. Areas with medium multifunctional degree were distributed from agricultural lands in the west of the study area to alongside the Yongding River and in the high-density built-up area in the east, resulting in a complex composition with high ratios of both agricultural land and parks. In contrast, areas with low multifunctionality formed a linear pattern along the potential risk areas corresponding to the pattern of risk mitigation hotspots, which was composed of a high proportion of built-up area, a relatively high proportion of attached green spaces, and generally single-function agricultural land.

Multifunctional GI types and characteristics

Relationship and associations of GI functions

The correlation coefficients of each function pair were all significant ($p < 0.01$) (Table 3). Habitat support (HS) had strongly positive correlations with urban heat island mitigation (UM) and with food and material provision (FP), but a moderately positive correlation with water conservation (WC) and a lower correlation with recreation (RE). Strongly positive correlations were also found for food and material provision (FP) with urban heat island mitigation (UM) and water conservation (WC). Other moderately positive correlations existed between water conservation (WC), urban heat island mitigation (UM), and recreation (RE). Even some weakly positive correlations existed between recreation and other functions, all of which described synergistic situations where both functions change in the same direction. Note that there were some moderately negative correlations between food and material provision and risk mitigation. The weak correlations between risk mitigation and urban heat island mitigation, habitat support, and water conservation indicated tradeoff situations where two functions were changing in opposite directions.

These positive correlations made it possible to identify spatial hotspot bundles of GI functions. The PCA analysis revealed main explanatory components for spatial hotspot bundles, which are presented in Table 4. Three principal components had eigenvalues greater than 1 for high multifunctional degree, which together explained 60.848% of the variance in the six functions (Table 4). The first principal component had higher loadings for recreation, urban heat island mitigation, risk mitigation, and water conservation, whereas the second principal component had higher loadings for habitat support, urban heat island mitigation, and water conservation, and the third had a higher loading for food and material provision (Table 5). In cells with medium multifunctional degree, the first two principal components with eigenvalues greater than 1 accounted for 69.916% of the variance (Table 4). The first principal component had higher loadings for urban heat island mitigation, habitat support, food and material provision, and water conservation, whereas the second principal component had higher loadings for risk mitigation and recreation (Table 5). In cells with low multifunctional degree, the first two principal components with eigenvalues greater than 1 contributed 53.793% of the variance (Table 4). The first principal component had higher loadings for food and material provision, habitat support, risk mitigation, water conservation, and urban heat island mitigation, whereas the second principal component had a higher loading for recreation (Table 5).

Bundle-based GI multifunctional types

Based on the seven principal components in Table 5 and on *k*-means cluster analysis, seven multifunctional types were identified across the study area (Fig. 6). The first three types were clustered from areas of high multifunctional degree; the next two types were clustered from areas of medium multifunctional degree; and the last two types were clustered from areas of low multifunctional degree. The radar diagrams in Fig. 6 show that all the multifunctional types were dominated by one or a few functions and had distinct heterogeneity of GI composition.

Type I, consisting of large area of natural woodland (Figs. 6a, 6b), had higher GI functions for water conservation, food and material provision, habitat support, and urban heat island mitigation, but lower functions for risk mitigation and recreation. This type was mainly located in the northwestern hilly areas. **Type II** was agglomerated in the northwestern area and had higher functions for recreation, water conservation, food and material provision, habitat support, and urban heat island mitigation, but lower functions for risk mitigation. Parks and forests were the main components of Type II areas (Fig. 6c). The scattered distribution of **Type III** corresponded to the spatial pattern of agricultural and forest patches (Fig. 6d), which provided a lower supply of water conservation and a higher supply of risk mitigation, recreation, urban heat island mitigation, habitat support, and food and material provision.

Table 3 Correlation coefficients of GI functions

	HS	WC	UM	RP	FP	RE
WC	0.434	–	–	–	–	–
UM	**0.618**	0.383	–	–	–	–
RP	− 0.085	− 0.144	− 0.093	–	–	–
FP	**0.516**	**0.521**	**0.506**	− 0.348	–	–
RE	0.280	0.165	0.303	0.123	0.188	–

$P < 0.01$ for all the correlation coefficients

Bold numbers represent strong correlations

Type IV had higher supplies of food and material provision, habitat support, and urban heat island mitigation functions, but lower functions for water conservation, risk mitigation, and recreation. This type mainly consisted of agricultural land (Fig. 6f) and forest (Fig. 6g) surrounding the northwestern hills and along the Yongding River (Fig. 6e), which were closely interlinked to high-density built-up areas. **Type V** mainly included water areas (Fig. 6h) and attached green spaces (Fig. 6i) in highly populated areas; it had a higher supply of risk mitigation and recreation, but less of other functions, including urban heat island mitigation and water conservation.

Type VI had a single large supply of risk mitigation, and its areas were distributed along railways and highways. It mainly consisted of attached green space, forests, and agricultural and other green patches (Fig. 6j), but was short of parks. Finally, **Type VII** had a single large supply of recreation and was mainly distributed in high-density built-up areas. Small-scale agricultural patches (Fig. 6k) and attached green space (Fig. 6l) were major contributors to this type.

Adaptive planning and design solutions to improve GI multifunctionality

According to the adaptive planning and design model illustrated in Fig. 2, appropriate GI actions and measures were proposed to preserve, restore, and embed levels for different multifunctional types. For GI within the same multifunctional degree, planning and management may be similar. Solutions will be introduced separately according to the GI multifunctional degree as described below.

Solutions for highly multifunctional areas: Types I, II, and III

GI elements in areas with high multifunctionality constitute the core areas of the GI network (Fig. 6). Preserving and restoring the functions of these GI elements is more important than embedding new GI elements in Types I, II, and III (Fig. 7).

Table 4 Statistical information for principal component analysis of the GI functions

Principal components	High multifunctionality			Medium multifunctionality			Low multifunctionality		
	Eigenvalues	% of variance	Cumulative % of variance	Eigenvalues	% of variance	Cumulative % of variance	Eigenvalues	% of variance	Cumulative % of variance
1	**1.339**	**22.317**	**22.317**	**2.606**	**43.428**	**43.428**	**2.198**	**36.628**	**36.628**
2	**1.308**	**21.795**	**44.112**	**1.589**	**26.488**	**69.916**	**1.030**	**17.165**	**53.793**
3	**1.004**	**16.736**	**60.848**	0.606	10.095	80.011	0.954	15.903	69.696
4	0.943	15.713	76.561	0.453	7.555	87.566	0.714	11.901	81.597
5	0.809	13.489	90.050	0.428	7.136	94.702	0.583	9.714	91.311
6	0.597	9.950	100.000	0.318	5.298	100.00	0.521	8.689	100.000

Bold numbers represent principal components with eigenvalues greater than 1

Table 5 Loadings of the principal components within each multifunctional degree

ES	Multifunctional degree						
	High multifunctionality			Medium multifunctionality		Low multifunctionality	
	PC 1	PC 2	PC 3	PC 1	PC 2	PC 1	PC 2
RP	**0.518**	− 0.294	0.443	0.195	**0.861**	− **0.635**	0.282
RE	− **0.614**	0.309	0.118	0.453	**0.567**	0.203	**0.648**
UM	**0.536**	**0.587**	0.373	**0.828**	0.287	**0.602**	0.464
WC	**0.512**	**0.506**	− 0.359	**0.539**	− 0.386	**0.628**	− 0.394
HS	− 0.380	**0.598**	0.470	**0.775**	− 0.243	**0.643**	0.316
FP	− 0.010	0.407	− **0.552**	**0.588**	− 0.486	**0.764**	− 0.245

Type I is characterized by forests in the northwestern hilly areas, including Qianling Hill. Preservation measures will be given top priority to sustain these high multiple functions, such as regularly closing hillsides or establishing natural reserves (Fig. 7a) to enhance water conservation capacity and habitat quality for hilly forest species such as *Parus venustulus*. In some degraded forest areas, preference will be given to native vegetation restoration engineering to increase the size of multifunctional areas and improve their connectivity. Miyawaki's ecological method for reforestation (Miyawaki 1998) is recommended here, and planting of local native plant species, e.g., *Fraxinus chinensis*, *Syringa pekinensis,* and *Potentilla flagellaris*, in multiple layers is suggested.

Type II mainly consists of large forest parks and urban parks, including Beigong National Forest Park and Beijing Garden of the World's Flowers. Besides preserving native habitats, some local historical and cultural sites will be considered a priority for preservation actions. Parks as an iconic part of the urban ecosystem are closely related to the daily life and leisure of residents. It is essential to restore the native plant community with visual aesthetic feeling and seasonal variation through enriching plant diversity, layering, and color (Fig. 7b). At the same time, artificial engineering measures such as fish-scale netting, vegetation planting, and lattice anchor reinforcement must be installed at sites with landslides or other geologic hazards, such as Qianling Hill and Beigong National Forest Park (Fig. 7c).

Type III mainly consists of forest patches on Qianling Hill in the west and along railways in the east. These scattered patches contribute to sustaining the connectivity and function of core areas. Emphasis was placed on preserving the existing vegetation community, including plant pruning and pest protection. Because these areas are weaker in terms of water conservation, it is important to restore green stormwater infrastructure to improve water conservation. Vegetation-based soil erosion control engineering

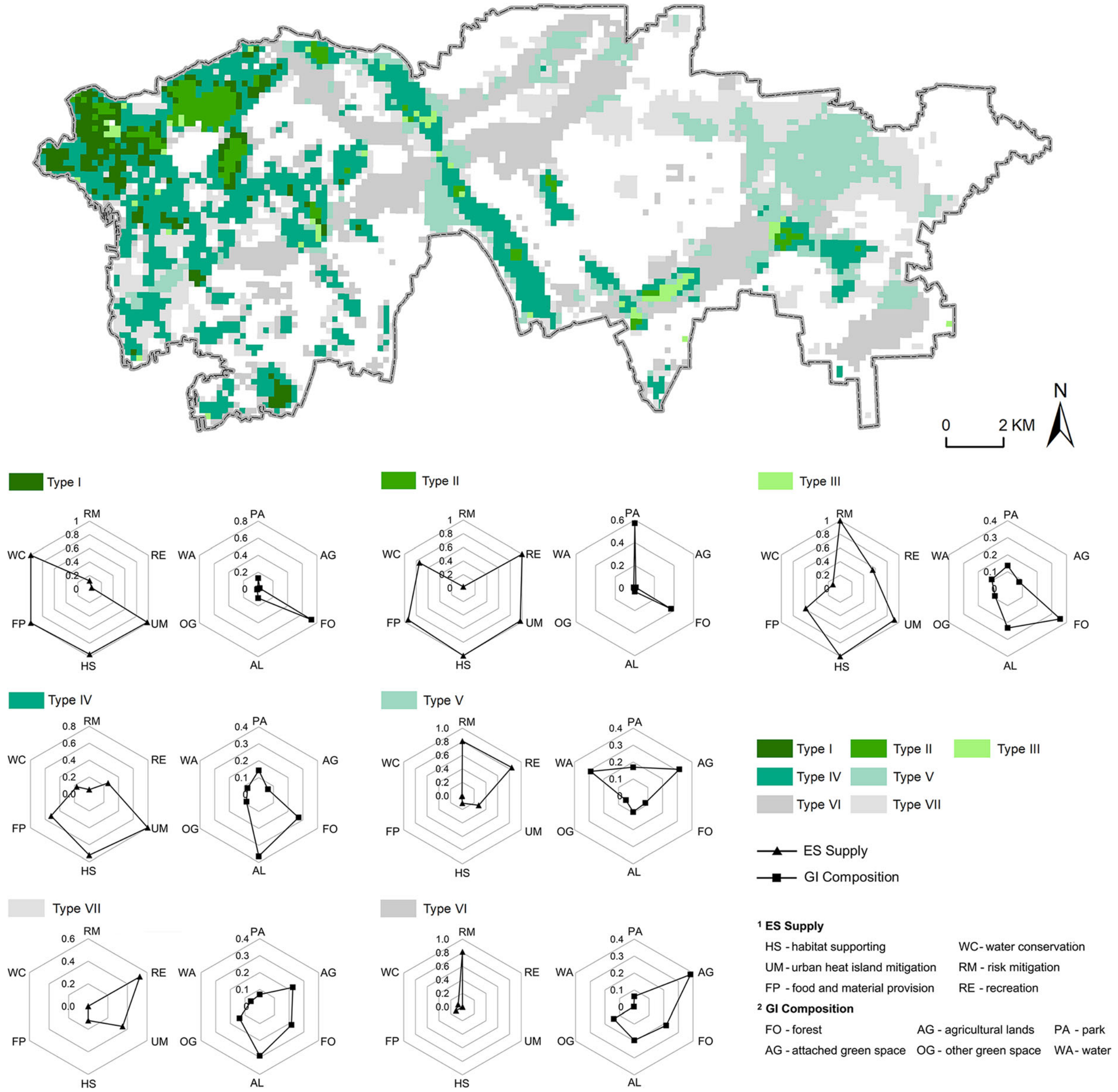


Fig. 6 Spatial patterns and characterizations of multifunctional types

measures are effective for forest patches on Qianling Hill with relatively high altitude and steep slopes, especially when increasing the percentage of local native plant species. For woodlands along railways, local rainwater harvesting engineering measures may be used to increase runoff collection capacity, such as the model-based vertical design of terrain and sunken lawn application (Fig. 7d).

Solutions for medium multifunctional areas: Types IV and V

GI elements in areas with medium multifunctionality are varied, involving croplands, wetlands along rivers, and urban and community parks, all of which constitute both hubs and corridors of the GI network. These GI elements provide more environmental regulation functions in the east, but more social functions in the west. Therefore, besides preserving the existing GI elements, it is important to restore and even embedding functions that are still weaker in areas of Types IV and V (Fig. 7).

In **Type IV** areas, aggregated patches distributed around the northwestern hills mainly consist of farmland and forest patches. In large patches along the central Yongding River, besides maintaining water quality and habitat by preserving riparian wetlands (Fig. 7e), historical sites such as the Early Moon of Lugou (dating from the Qing Dynasty) should be preserved. Environmentally friendly facilities can also improve social benefits and residents' wellbeing. For example, tourism-oriented agricultural restoration may contribute to improving the social and cultural functions of farmlands, such as picking orchards, sightseeing gardens, and leisure parks (Fig. 7f). Wooded trails may be used in forest sites for low-impact leisure activities such as hiking and birdwatching (Fig. 7g). Boardwalks, viewing decks, and biodiversity signage should be added to enhance leisure and aesthetic values along the river. Furthermore, for parks scattered in the western areas, stormwater harvesting engineering technologies such as bioretention, permeable pavers, and disconnected downspouts (Dietz 2007; Baek et al. 2015) can be used for stormwater management to enhance the risk mitigation and water conservation functions.

For **Type V** areas, besides preserving existing green patches in built-up areas, nature-based approaches such as plant community structure rebuilding and vertical greening or green roofs (Fig. 7i) can be used to improve regulating functions in limited attached green spaces. Because the Liangshui River and the green buffers along it are narrow, straight, and closely linked with roads, rehabilitating the wetland community along the riverside (Fig. 7h) should have high priority. It would be advisable to use native plant species and softer engineering approaches and materials such as wood and pebbles.

Solutions for areas of low multifunctional degree: Types VI and VII

GI elements in areas with low multifunctionality are located in built-up areas and are made up of small, disconnected attached green spaces, agricultural land, or forest patches. They always serve a single function. Restoring the multiple functions of existing GI elements and embedding new GI elements are urgent for Types VI and VII (Fig. 7).

Type VI areas distributed along transportation lines consist of attached green spaces that are planned to suppress traffic noise rather than enhancing aesthetic values. Therefore, it is critical to emphasize rebuilding

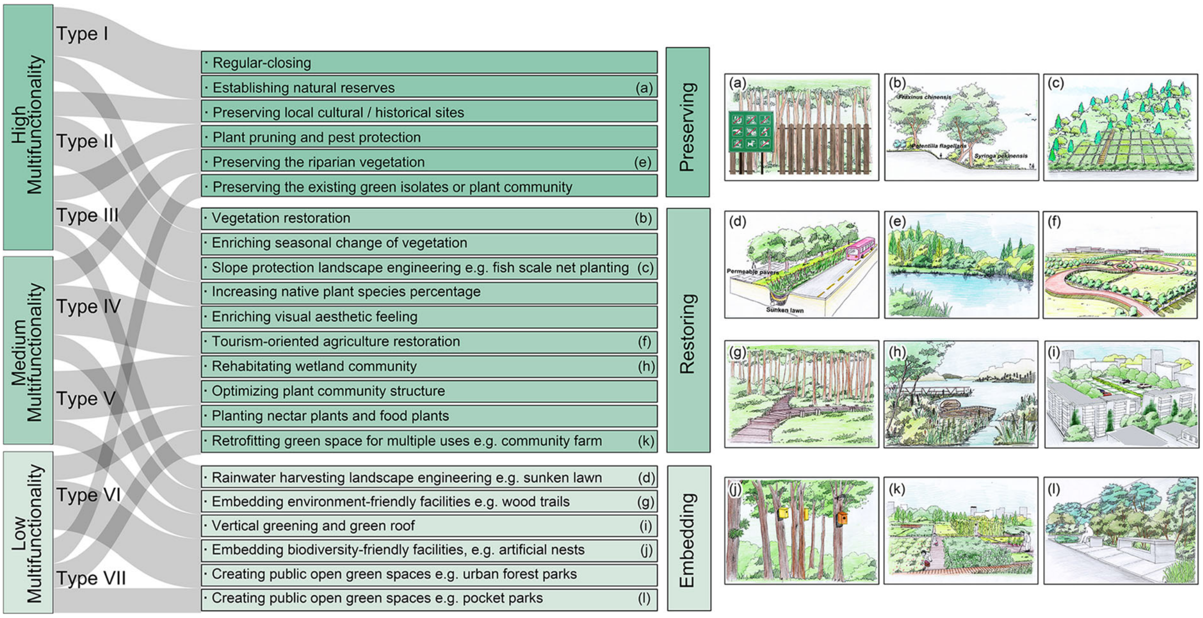


Fig. 7 Adaptive planning and design solutions to improve GI multifunctionality

the plant community structure to enhance regulation functions such as noise mitigation and urban heat island mitigation. At the same time, plant landscaping measures that enrich the inventory of plant species are necessary to provide varied visual experiences for drivers and passengers. Measures like planting nectar and food plants and building artificial nests can provide habitats for wildlife and increase biodiversity (Fig. 7j).

Type VII areas, which are made up of agricultural land and attached green spaces scattered in the eastern built-up areas, provide high recreation and urban heat island mitigation, but less of other functions. It is suggested to transform and extend the agricultural lands into community farms (Fig. 7k) to enhance the supply of food and material provision and of recreation simultaneously. Moreover, urban forest parks, pocket parks (Fig. 7l), and other small-scale GI sites need to be embedded across densely built-up areas to improve GI network connectivity and to provide leisure space for residents and habitat for insects and migrating birds.

Discussion

Bridging the gap between landscape ecological science and urban planning practice

Human activities have changed the landscape pattern of urban ecosystems, leading to both positive and negative impacts on human well-being. This complex contradiction has become a conspicuous challenge for sustainable development in urban areas, which begs for interdisciplinary participation and discussion (Opdam et al. 2018; Wu 2019). The multifunctional characterization of GI in Fengtai indicates the improvement of GI functions after rapid urban development. GI design and management must be based on scientific knowledge. The pattern–process–design paradigm proposed by Nassauer provides a new perspective to link scientific theory and social practice (Nassauer and Opdam 2008; Wang et al. 2014), although landscape ecological knowledge has been seldom used as fully as it could be in urban planning practice due to the gaps between various disciplines (Opdam et al. 2006).

This study proposes a procedure for mapping, characterizing, and improving multiple GI functions based on assessing ES from GI components (Fig. 2). This GI-based study contributes a spatial perspective that can support the pattern–process–design paradigm. This study has integrated physical properties with the spatial pattern of the GI network in the Fengtai District to assess and map GI multifunctional degree, thus linking pattern and process. Potential landscape planning and design solutions were then matched to the locations of multifunctional GI types, making the linkage of process and design possible. Design has been considered here as a part of scientific research instead of a subjective process, contributing to the optimization of GI pattern and process. Although the result may be insufficient for decision-makers in complex urban ecosystems, it will advance our understanding of the relationships between landscape ecological studies and urban planning practices. This study highlights that knowledge of landscape patterns, processes, and functions in landscape ecological science might offer insights into landscape planning, design, and management to improve human well-being, if translated into the planning and design language used by urban managers, planners, and landscape designers.

Implications for GI planning and design practice

Although the potential of GI planning to combine ecological and social functions is broadly acknowledged (Mell 2009) and many possible solutions have often been used (examples listed in Fig. 4), the multifunctional characterization of GI is far from well understood by planners and designers. The plentiful findings of ecological science have yet to be fully applied in landscape practice because poor communication between ecological science and landscape practice has hindered the application of research findings to decision-making.

Multifunctionality in the context of urban planning and design means the sustained provision of multiple functions from GI (Ahern 2013). Unlike traditional GI decision-making, which mainly aims to optimize areal and spatial patterns, multifunctionality emphasizes the synergies of multiple landscape functions through spatially based planning and management methods (Peng et al. 2019). Hansen et al. (2019), by comparing multifunctional planning methods in Germany, the United Kingdom, and Denmark, found that the current evaluation of multifunctionality is relatively basic.

There are distinctive differences between academic multifunctionality analyses and planning practices. Some researchers have proposed frameworks and suggestions for GI planning and management. Lovell and Taylor (2013) proposed combining the perceptions of residents with those of experts in multifunctional landscape planning, to help decision-makers comprehensively consider the current and potential multifunctionality of landscapes. Although it has been suggested to integrate landscape multifunctional standards into urban planning and policies in the future, it remains challenging to design adaptive solutions for specific spatial sites to improve their multifunctionality.

The indiscriminate encouragement of high multifunctional degree is impossible, especially in urban areas with relatively high land-use intensity (Hansen et al. 2019). Hence, planning guidance combined with site-design solutions are likely options for arranging multifunctional GI spatially and temporally. In this study, the multifunctional degree implies the capacity of GI to provide multiple functions, whereas the multifunctional type system goes a step further to show the heterogeneous performance of GI in benefiting urban ecosystems and human beings. Corresponding to the characterization of multifunctional types and their location, an adaptive model (Fig. 4) was designed to help plan and design such solutions for specific sites to improve the multifunctionality of the complete GI entity. Solutions to preserve, restore, and embed GI and its functions have been adaptively used in local GI development practice, as shown in Fig. 7. In general, preserving existing green spaces and native plant communities at the beginning is preferable to restoring them after loss or degradation or to embedding new ones. All solutions should be contextualized within the local requirements for improving multiple GI functions (Fig. 7). For instance, regularly closing the core habitat of focused species to limit the human disturbance is crucial for Type I (Fig. 7a), whereas retrofitting existing green isolates and embedding new GI elements is important for Types V and VII (Fig. 7h, i). Overall, mapping and characterizing GI multifunctionality will provide urban planners with powerful evidence for identifying clear targets and spatial sites to develop the GI entity. The adaptive model proposed in this paper effectively combines multifunctional analyses and GI practices and provides a series of feasible planning and design solutions that are closely linked with GI decision-making, making it possible to improve GI multifunctionality in different scenarios.

Limitations and future research prospects

Due to data and model limitations, the present assessment of ES and the method of mapping GI multifunctionality have their limitations, too. Moreover, the number and type of focused functions will also affect the multifunctionality results. Despite these limitations and uncertainties, this paper has revealed how existing GI benefits cities and human beings, where and which GI elements can provide higher multiple function sets, and which types of functions have high or low values. This paper has emphasized the complexity and necessity of mapping and characterizing GI multifunctionality and has made it possible to bring adaptive planning and design solutions into GI management. It will be essential in future research to establish comprehensive and uniformly standard assessment approaches to understand multiple ES functions fully.

In this study, ES diversity has been considered as a measure of multifunctionality, and the importance of ensuring the provision of multiple functions has been highlighted by regarding all functions as equally weighted. The current view on GI decision-making is to increase and maintain the multifunctionality of all GI components as much as possible. However, this may not be cost-effective because the required functions cannot be homogeneous all over the city and it is impossible to raise all areas to a high multifunctional degree.

Furthermore, it can be argued that ES differ in their contribution to human well-being and that the same function may be valued differently by different groups of people in the same area depending on their education level, personal income, and individual experience (Casado-Arzuaga et al. 2013). It is important to integrate stakeholder perspectives into ES assessments (Diaz et al. 2011; Ernstson 2013). Although the current GI function and composition characteristics of the seven multifunctional types and the proposed series of feasible planning and design solutions have been closely linked with actual site condition and requirements, the need for specific functions versus multifunctionality by different stakeholders has been ignored in multifunctional analyses.

It is therefore suggested that stakeholders' perspectives on multiple functions might be considered in future research and highlighted in multifunctionality mapping for sustainable GI planning and management.

Conclusions

This study introduced landscape ecological science into GI planning to improve GI multifunctionality. Six GI functions were assessed and mapped to describe GI multifunctionality in the Fengtai District of Beijing, China by means of ES assessment. GI function hotspots were identified, and function bundles were detected. Seven multifunctional types were classified and characterized by their distinct heterogeneity of compositions and function sets, which represented specific planning and design orientations in GI practice. In correspondence with the characterization of multifunctional types and their location, this study designed an adaptive model and provided feasible planning and design solutions. The results can help GI planners effectively determine optimal solutions according to actual site characteristics and improve GI multifunctionality. By improving the performance of the GI entity through mapping and characterizing GI multifunctionality, this study offers insights into how to bridge the gap between landscape ecological science and urban planning.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by YW and QC. The first draft of the manuscript was written by YW, QC and PF. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

Adams WM (2014) The value of valuing nature. Science 346:549–551

Ahern J (2011) From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landsc Urban Plan 100:341–343. https://doi.org/10.1016/j.landurbplan.2011.02.021

Ahern J (2013) Urban landscape sustainability and resilience: the promise and challenges of integrating ecology with urban planning and design. Landsc Ecol 28:1203–1212. https://doi.org/10.1007/s10980-012-9799-z

Anselin L (1995) Local Indicators of Spatial Association-LISA. Geogr Anal 2:93–115

Artmann M, Bastian O, Grunewald K (2017) Using the concepts of green infrastructure and ecosystem services to specify Leitbilder for compact and green cities—the example of the landscape plan of Dresden (Germany). Sustainability (Basel) 9:198. https://doi.org/10.3390/su9020198

Baek S, Choi D, Jung J, Lee H, Lee H, Yoon K, Cho KH (2015) Optimizing low impact development (LID) for stormwater runoff treatment in urban area, Korea: Experimental and modeling approach. Water Res 86:122–131. https://doi.org/10.1016/j.watres.2015.08.038

Baró F, Haase D, Gómez-Baggethun E, Frantzeskaki N (2015) Mismatches between ecosystem services supply and demand in urban areas: a quantitative assessment in five European cities. Ecol Indic 55:146–158. https://doi.org/10.1016/j.ecolind.2015.03.013

Beijing Municipal Bureau of Statistics (2019) Statistical Yearbook of Fengtai District (2015, 2016, 2017), Beijing. Available from: bjft.gov.cn/ftq/2015zhh/list.shtml (in Chinese)

Benedict MA, McMahon ET (2002) Green infrastructure: smart conservation for the 21st century. Renew Resour J 3:12–17

Boyd J, Banzhaf S (2007) What are ecosystem services? The need for standardized environmental accounting units. Ecol Econ 63:616–626. https://doi.org/10.1016/j.ecolecon.2007.01.002

Bryan BA, Raymond CM, Crossman ND, Macdonald DH (2010) Targeting the management of ecosystem services based on social values: where, what, and how? Landsc Urban Plan 97:111–122. https://doi.org/10.1016/j.landurbplan.2010.05.002

Cameron RWF, Blanuša T, Taylor JE, Salisbury A, Halstead AJ, Henricot B, Thompson K (2012) The domestic garden—its contribution to urban green infrastructure. Urban Urban Green 11:129–137. https://doi.org/10.1016/j.ufug.2012.01.002

Cardinale BJ et al (2012) Biodiversity loss and its impact on humanity. Nature 486:59–67. https://doi.org/10.1038/nature11148

Casado-Arzuaga I, Madariaga I, Onaindia M (2013) Perception, demand and user contribution to ecosystem services in the Bilbao Metropolitan Greenbelt. J Environ Manag 129:33–43. https://doi.org/10.1016/j.jenvman.2013.05.059

Chang Q, Liu X, Wu J, He P (2015) MSPA-based urban green infrastructure planning and management approach for urban sustainability: case study of Longgang in China. J Urban Plan Dev. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000247

Diaz S, Quetier F, Trainor SF, Caceres DM (2011) Reply to Romero and Agrawal: unpacking the specific links between biodiversity, ecosystem services, and social diversity is an essential first step. Proc Natl Acad Sci USA 108:E197. https://doi.org/10.1073/pnas.1104742108

Dietz ME (2007) Low impact development practices: a review of current research and recommendations for future directions. Water Air Soil Pollut 186:351–363. https://doi.org/10.1007/s11270-007-9484-z

Ernstson H (2013) The social production of ecosystem services: a framework for studying environmental justice and ecological complexity in urbanized landscapes. Landsc Urban Plan 109:7–17. https://doi.org/10.1016/j.landurbplan.2012.10.005

Fagerholm N, Käyhkö N, Ndumbaro F, Khamis M (2012) Community stakeholders' knowledge in landscape assessments—mapping indicators for landscape services. Ecol Indic 18:421–433. https://doi.org/10.1016/j.ecolind.2011.12.004

Gong L, Mao B, Qi Y, Xu C (2015) A satisfaction analysis of the infrastructure of country parks in Beijing. Urban Urban Green 14:480–489. https://doi.org/10.1016/j.ufug.2015.04.013

Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM (2008) Global change and the ecology of cities. Science 319:756–760. https://doi.org/10.1126/science.1150195

Haase D, Schwarz N, Strohbach M, Kroll F, Seppelt R (2012) Synergies, trade-offs, and losses of ecosystem services in urban regions: an integrated multiscale framework applied to the Leipzig-Halle Region, Germany. Ecol Soc. https://doi.org/10.5751/ES-04853-170322

Hansen MH, Li H, Svarverud R (2018) Ecological civilization: Interpreting the Chinese past, projecting the global future. Glob Environ Chang 53:195–203. https://doi.org/10.1016/j.gloenvcha.2018.09.014

Hansen R, Olafsson AS, van der Jagt APN, Rall E, Pauleit S (2019) Planning multifunctional green infrastructure for compact cities: what is the state of practice? Ecol Indic 96:99–110. https://doi.org/10.1016/j.ecolind.2017.09.042

Hansen R, Pauleit S (2014) From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. Ambio 43:516–529. https://doi.org/10.1007/s13280-014-0510-2

Herzog CP (2016) A multifunctional green infrastructure design to protect and improve native biodiversity in Rio de Janeiro. Landsc Ecol Eng 12:141–150. https://doi.org/10.1007/s11355-013-0233-8

Hoerbinger S, Immitzer M, Obriejetan M, Rauch HP (2018) GIS-based assessment of ecosystem service demand concerning green infrastructure line-side vegetation. Ecol Eng 121:114–123. https://doi.org/10.1016/j.ecoleng.2017.06.030

Lalor GC, Zhang C (2001) Multivariate outlier detection and remediation in geochemical databases. Sci Total Environ 281:99–109. https://doi.org/10.1016/S0048-9697(01)00839-7

Liu Z, Lin Y, De Meulder B, Wang S (2019) Can greenways perform as a new planning strategy in the Pearl River Delta, China. Landsc Urban Plan. https://doi.org/10.1016/j.landurbplan.2019.03.012

Lovell ST, Taylor JR (2013) Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landsc Ecol 28:1447–1463. https://doi.org/10.1007/s10980-013-9912-y

Malinga R, Gordon LJ, Jewitt G, Lindborg R (2015) Mapping ecosystem services across scales and continents—a review. Ecosyst Serv 13:57–63. https://doi.org/10.1016/j.ecoser.2015.01.006

Manchester City Council (2015) Draft Manchester Green and Blue Infrastructure Strategy. Neighborhoods Scrutiny Committee, Manchester

Marsboom C, Vrebos D, Staes J, Meire P (2018) Using dimension reduction PCA to identify ecosystem service bundles. Ecol Indic 87:209–260. https://doi.org/10.1016/j.ecolind.2017.10.049

Meerow S (2020) The politics of multifunctional green infrastructure planning in New York City. Cities 100:102621. https://doi.org/10.1016/j.cities.2020.102621

Meerow S, Newell JP (2017) Spatial planning for multifunctional green infrastructure: growing resilience in Detroit. Landsc Urban Plan 159:62–75. https://doi.org/10.1016/j.landurbplan.2016.10.005

Mell IC (2009) Can green infrastructure promote urban sustainability? Eng Sustain 162:23–34. https://doi.org/10.1680/ensu.2009.162.1.23

Mell IC, Henneberry J, Hehl-Lange S, Keskin B (2013) Promoting urban greening: Valuing the development of green infrastructure investments in the urban core of Manchester, UK. Urban Urban Green 12:296–306. https://doi.org/10.1016/j.ufug.2013.04.006

Mexia T et al (2018) Ecosystem services: urban parks under a magnifying glass. Environ Res 160:469–478. https://doi.org/10.1016/j.envres.2017.10.023

Miyawaki A (1998) Restoration of urban green environments based on the theories of vegetation ecology. Ecol Eng 11:157–165. https://doi.org/10.1016/S0925-8574(98)00033-0

Nassauer JI, Opdam P (2008) Design in science: extending the landscape ecology paradigm. Landsc Ecol 23:633–644. https://doi.org/10.1007/s10980-008-9226-7

Nelson E et al (2009) Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Front Ecol Environ 7:4–11. https://doi.org/10.1890/080023

Ni S, Ma C, Yang H, Zhang Y (2018) Spatial distribution and susceptibility analysis of avalanche, landslide and debris flow in Beijing mountain region. J Beijing For Univ 40:81–91 **(in Chinese)**

Opdam P, Luque S, Nassauer J, Verburg PH, Wu J (2018) How can landscape ecology contribute to sustainability science? Landsc Ecol 33:1–7. https://doi.org/10.1007/s10980-018-0610-7

Opdam P, Steingröver E, Rooij SV (2006) Ecological networks: a spatial concept for multi-actor planning of sustainable landscapes. Landsc Urban Plan 75:322–332. https://doi.org/10.1016/j.landurbplan.2005.02.015

Peng J, Chen X, Liu Y, Lü H, Hu X (2016) Spatial identification of multifunctional landscapes and associated influencing factors in the Beijing-Tianjin-Hebei region, China. Appl Geogr 74:170–181. https://doi.org/10.1016/j.apgeog.2016.07.007

Peng J, Liu Y, Liu Z, Yang Y (2017) Mapping spatial nonstationarity of human-natural factors associated with agricultural landscape multifunctionality in Beijing–Tianjin–Hebei region, China. Agric Ecosyst Environ 246:221–233. https://doi.org/10.1016/j.agee.2017.06.007

Peng J, Hu X, Qiu S, Hu Y, Meersmans J, Liu Y (2019) Multifunctional landscapes identification and associated development zoning in mountainous area. Sci Total

Environ 660:765–775. https://doi.org/10.1016/j.scitotenv.2019.01.023

People's Government of Beijing Municipality (2019) Government Work Report, Beijing. Available from: beijing.gov.cn/zhengce/zhengcefagui/201905/t20190522_61777.html (in Chinese)

People's Government of Beijing Municipality (2017) Territory Development Plan of Fengtai (2017–2035), Beijing. Available from: bjft.gov.cn/so/s?qt=2035&siteCode=1101060001 (in Chinese)

Plieninger T, Dijks S, Oteros-Rozas E, Bieling C (2013) Assessing, mapping, and quantifying cultural ecosystem services at community level. Land Use Policy 33:118–129. https://doi.org/10.1016/j.landusepol.2012.12.013

Pulighe G, Fava F, Lupia F (2016) Insights and opportunities from mapping ecosystem services of urban green spaces and potentials in planning. Ecosyst Serv 22:1–10. https://doi.org/10.1016/j.ecoser.2016.09.004

Qiu J, Turner MG (2013) Spatial interactions among ecosystem services in an urbanizing agricultural watershed. Proc Natl Acad Sci USA 110:12149–12154. https://doi.org/10.1073/pnas.1310539110

Quintas-Soriano C, Castro AJ, García-Llorente M, Cabello J, Castro H (2014) From supply to social demand: a landscape-scale analysis of the water regulation service. Landsc Ecol 29:1069–1082

Raudsepp-Hearne C, Peterson GD, Bennett EM (2010) Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc Natl Acad Sci USA 107:5242–5247. https://doi.org/10.1073/pnas.0907284107

Raymond CM, Bryan BA, MacDonald DH, Cast A, Strathearn S, Grandgirard A, Kalivas T (2009) Mapping community values for natural capital and ecosystem services. Ecol Econ 68:1301–1315. https://doi.org/10.1016/j.ecolecon.2008.12.006

Rottle ND (2006) Factors in the landscape-based greenway: a Mountains to Sound case study. Landsc Urban Plan 76:134–171. https://doi.org/10.1016/j.landurbplan.2004.09.039

Ryan RL (2011) The social landscape of planning: Integrating social and perceptual research with spatial planning information. Landsc Urban Plan 100:361–363. https://doi.org/10.1016/j.landurbplan.2011.01.015

Schäffler A, Swilling M (2013) Valuing green infrastructure in an urban environment under pressure—the Johannesburg case. Ecol Econ 86:246–257. https://doi.org/10.1016/j.ecolecon.2012.05.008

Sun Y, Zhou X, Zheng G, Li J, Shi H, Guo Z, Du J (2017) Carbon monoxide degassing from seismic fault zones in the Basin and Range province, west of Beijing, China. J Asian Earth Sci 149:41–48. https://doi.org/10.1016/j.jseaes.2017.07.054

Sussams LW, Sheate WR, Eales RP (2015) Green infrastructure as a climate change adaptation policy intervention: muddying the waters or clearing a path to a more secure future? J Environ Manag 147:184–193. https://doi.org/10.1016/j.jenvman.2014.09.003

Tzoulas K, Korpela K, Venn S, Yli-Pelkonen V, Kaźmierczak A, Niemela J, James P (2007) Promoting ecosystem and human health in urban areas using Green Infrastructure: a literature review. Landsc Urban Plan 81:167–178. https://doi.org/10.1016/j.landurbplan.2007.02.001

Vannier C et al (2019) Mapping ecosystem services bundles in a heterogeneous mountain region. Ecosyst People 15:74–88. https://doi.org/10.1080/26395916.2019.1570971

Wang Z (2018) Evolving landscape-urbanization relationships in contemporary China. Landsc Urban Plan 171:30–41. https://doi.org/10.1016/j.landurbplan.2017.11.010

Wang Z, Tan PY, Zhang T, Nassauer JI (2014) Perspectives on narrowing the action gap between landscape science and metropolitan governance: practice in the US and China. Landsc Urban Plan 125:329–334. https://doi.org/10.1016/j.landurbplan.2014.01.024

Weber T, Sloan A, Wolf J (2006) Maryland's Green Infrastructure Assessment: development of a comprehensive approach to land conservation. Landsc Urban Plan 77:94–110. https://doi.org/10.1016/j.landurbplan.2005.02.002

Wu J (2019) Linking landscape, land system and design approaches to achieve sustainability. J Land Use Sci. https://doi.org/10.1080/1747423X.2019.1602677

Wu K, Fang C, Zhao M, Chen C (2013) The intercity space of flow influenced by high-speed rail: a case study for the rail transit passenger behavior between Beijing and Tianjin. Acta Geogr Sin 68:159–174 **(in Chinese)**

Wu J, Feng Z, Gao Y, Peng J (2013) Hotspot and relationship identification in multiple landscape services: a case study on an area with intensive human activities. Ecol Indic 29:529–537. https://doi.org/10.1016/j.ecolind.2013.01.037

Yang J, Zhou J (2007) The failure and success of greenbelt program in Beijing. Urban Urban Green 6:287–296. https://doi.org/10.1016/j.ufug.2007.02.001

Yu Z, Liu X, Zhang J, Xu D, Cao S (2018) Evaluating the net value of ecosystem services to support ecological engineering: framework and a case study of the Beijing Plains afforestation project. Ecol Eng 112:148–152. https://doi.org/10.1016/j.ecoleng.2017.12.017

Zhao X (2014) Beijing Birds Illustrations. Beijing Normal University Press, Beijing (in Chinese)

Zhou C (2010) Common animal illustrations in the wild. Higher Education Press, Beijing (in Chinese)